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WOOD AND OTHER RENEWABLE RESOURCES

Production and energetic utilization of wood from short rotation coppice—a life cycle assessment

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Abstract
Purpose Ambitious targets for the use of renewable energy have recently been set in the European Union. To reach these targets, a large share of future energy generation will be based on the use of woody biomass. Therefore, there is an increasing interest in the cultivation of fast-growing tree species on agricultural land outside forests. Intensive crop production is always considered to harm the environment. The study explores the environmental burdens of the cultivation of fast-growing tree species on agricultural land and their subsequent energetic conversion in comparison to the fossil reference energy system.
Methods Life cycle assessment (LCA) methodology according to the ISO 14040 and 14044 is used. Input data were partly collected within the German joint research project AGROWOOD. Two utilization paths of short rotation poplar chips are analyzed: heat and power generation in a cogeneration plant and the production of Fischer–Tropsch (FT) diesel. Subsequently, the bioenergy systems are compared with their fossil references.
Results and discussion The production and distribution of 1 oven dry tonne (odt) of short-rotation poplar chips require 432 MJ non-renewable energy. This equals an output–input ratio of 43:1, which includes all process steps from field preparation to road transport. Emissions of this energy use amount to a global warming potential of 38.4 kg CO_2 eq odt^{-1}, an acidification potential of 0.24 kg SO_2 eq odt^{-1}, and a eutrophication potential of 0.04 kg PO_4 eq odt^{-1}. The greatest reductions of environmental impacts can be achieved by substituting power from lignite with cogenerated power from short-rotation coppice (SRC). Compared with the average German power generation mix GWP and AP of power generation from short rotation poplar chips are lower by 97% and 44%, respectively, while eutrophication potential is about 26% higher. FT diesel made from short-rotation poplar chips has an 88% lower global warming potential and a 93% lower acidification potential than fossil diesel. But, the eutrophication potential of FT diesel is twice as high as of fossil diesel.
Conclusions It was found that even intensively produced wood from SRC can reduce environmental burdens if it is used for biofuel instead of fossil fuel. The utilization of the same amount of short-rotation poplar chips for heat and power production causes fewer environmental impacts than its use for FT diesel.

Keywords AGROWOOD · Biomass · Energy balance · Eutrophication potential · Fischer–Tropsch diesel · Fuel wood · GWP (global warming potential) · Renewable energy · Short-rotation poplar

1 Introduction

Recent decisions in European environmental policy to increase the share of renewable energy (European Commission 2008) will lead to an increased demand for fuel wood. Studies (Ochs et al. 2007; Mantau et al. 2007) forecast a shortage in the future German wood supply from traditional sources and predict an increasing relevance of wood grown outside of forests. Energy supplier and automotive companies started to focus on short-rotation coppice (SRC) cultivation to ensure their future resource

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supply. Recently, some thousand hectares of short-rotation plantations have been established in Germany.

Growing public awareness and the discussion on sustainability criteria of biofuel production on EU level (European Commission 2008) require the assessment of the environmental consequences of intensively grown biomass and its utilization paths. If bioenergy is used for substitution, its production should not exceed environmental impacts of the fossil alternative. The life cycle assessment (LCA) method is used to investigate the environmental impacts of production and the energetic utilization of short-rotation wood. The study evaluates the short-rotation poplar production in central Europe, with a special focus on the eastern part of Germany. The conversion paths of the biomass considered are combustion in a CHP plant and conversion into Fischer–Tropsch (FT) diesel. The results of the environmental assessment will be compared with the environmental impacts of the fossil counterpart. The present paper contributes to the assessment of the environmental profile of wood from different sources for material or energetic use as called for by Werner and Nebel (2007).

Previous studies mostly focused on the greenhouse gas and energy balance of the short-rotation biomass systems (Goglio and Owende 2009; Adler et al. 2007; Lettens et al. 2003; Matthews 2001; Jungmeier and Spitzer 2001; Dubuisson and Sintzoff 1998; Börjesson 1996). Only few of them examined further impact categories like acidification and eutrophication (Gasol et al. 2009; Carpentieri et al. 2005; Heller et al. 2003; Rafaschieri et al. 1999). Most of the studies have been carried out on short-rotation willow (*Salix* sp.) and focus on Western Europe or the USA. First results on the LCA of the production of poplar chips from SRC have been published in German in Rödl (2008). Here, a brief report of the updated results of the production assessment is presented, as well as the LCA on the utilization of the poplar chips.

2 Materials and methods

The study was carried out following the guidelines of ISO 14040 and 14044 (DIN 2006). The calculation and modeling were done with the help of the software program GaBi 4 (PE, LBP 1992–2008). General data on standard grid electricity production, fuel and lubricant oil extraction, and raw material and fossil energy carrier production were taken from the GaBi 4 database (PE, LBP 1992–2008). The CML 2001 method of Guinée (2002) has been adopted for impact assessment. Four categories have been chosen to assess the environmental impacts of the short-rotation biomass system:

– Global warming potential (GWP)
– Eutrophication potential (EP)
– Acidification potential (AP)
– Photo-oxidant creation potential (POCP)

Acidification potential, global warming potential, and photochemical ozone formation are the most important categories for biomass cultivation and distribution. The eutrophication potential as well as the toxicity potential are less important on a common scale. The impact indicators for toxicity might be only partly reliable because of methodological uncertainties (Reap et al. 2008). The current toxicity models provide characterization factors, which often differ considerably. It is difficult to predict the fate of a released substance, the rate of its intake by humans and the resulting effects (Finnveden et al. 2009; Rosenbaum et al. 2008). For that reason, the impact categories of toxicity are not considered in the presented assessment.

As Guinée et al. (2009) stated in their paper, special attention has to be drawn on the accounting of biogenic carbon dioxide. Atmospheric CO_2 fixed during the wood growth is on the input side. The same carbon is finally released to the atmosphere during the combustion. In- and output add up to zero. This is only valid if the biomass resource is used in a sustainable manner.

2.1 System boundaries and functional units

The study is divided into two parts. The first part assesses the environmental impacts of short-rotation poplar wood production, considering the biomass production system from soil preparation to the harvest of biomass, as well as its drying and transportation. Carbon dioxide uptakes in the soil or CO_2 emissions from the soil are not included into the impact assessment. In chapter 3.1.3 the quantification of carbon stock changes in the soil will be discussed. All energy and material flows during the entire lifespan of the plantation are allocated evenly to the biomass produced. System boundaries of the first part comprise biomass production including its supply chain. The functional unit is 1 oven dry tonne (odt) of poplar chips.

The second part of the study assesses the whole biomass production chain and the subsequent energy conversion. This includes the cultivation and processing of biomass, its drying, its transport to the production site, and its conversion into heat, power, or FT diesel fuel. All direct and indirect consumption of fossil energy and its environmental impact is accounted for. The functional unit in the second part of this study is 1 MJ power, 1 MJ heat, and 1 MJ FT diesel, used in a mid-range car, respectively. Figure 1 displays the system boundaries of the whole bioenergy system, which is assessed in the second part of the study.

The study includes all direct inputs during the life cycle of short-rotation wood, like fossil energy use of machinery

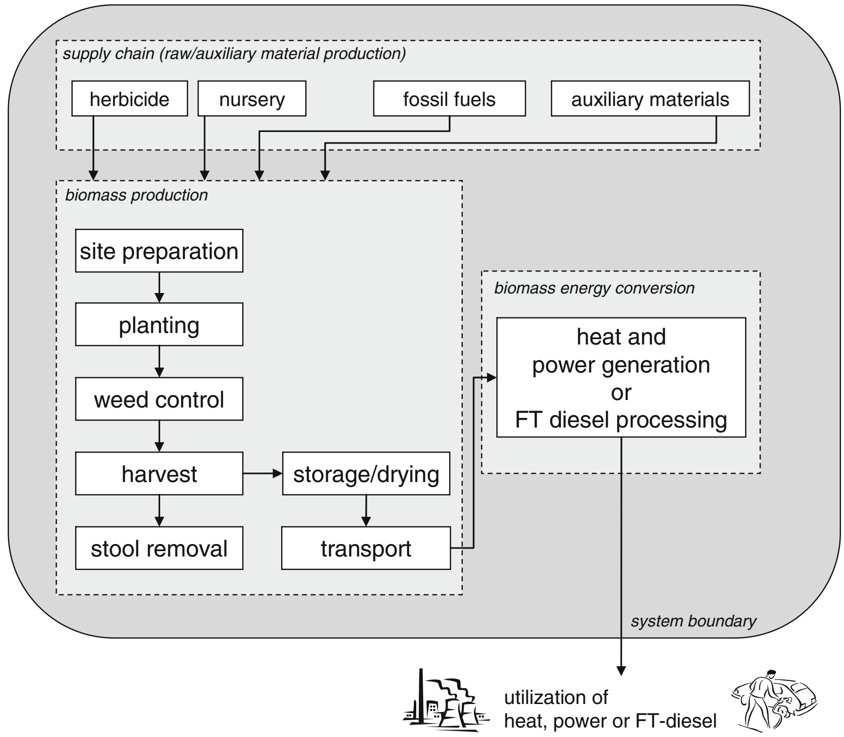


Fig. 1 System boundaries of the assessment of the whole bioenergy system, namely heat and power generation or FT diesel production from short-rotation poplar chips, with the functional unit 1 MJ

and other auxiliary materials. But, material and energy use embodied in fuels, herbicides, and other auxiliary materials are also covered by the system boundaries. Energy from solar radiation, and water and carbon dioxide used for photosynthesis are recorded by the inventory but do not contribute to the impact categories.

2.2 Modeling of biomass production and delivery

Biomass production and delivery starts with soil preparation and ends with the delivery of the wood chips to the conversion facility.

The poplar cuttings are planted on a plowed and harrowed agricultural site. A glyphosate herbicide is sprayed before planting. In the first year, mechanical weed control is considered. There is no use of fertilizers integrated in the model. It was found in field trials that poplar growth does not respond to fertilizer application (Kauter et al. 2001; Röhricht and Ruscher 2004; Boelke 2006). For non-fertilized sites, long-term monitoring showed no significant decline in soil nitrogen (Knust 2007). The core of the biomass production model is the biological production of wood, which represents the photosynthesis. Within this model, wood is produced from water, carbon dioxide, and solar radiation. The required input masses per tonne short-rotation wood are quantified with the help of the model from Zimmer and Wegener (1996). According to the balance of the chemical photosynthesis equation, this model calculates the amounts of inputs like water and CO_2. The input of solar radiation is deduced from the lower heating value (H_i) of the wood.

The plantation is harvested every 4 years. There are five harvests during the whole lifetime of the plantation. The yield amounts to 8 odt per hectare and year. It is assumed that the stools are removed after 20 years, and the field is reconverted into arable land. After harvesting, the poplar chips are dried in piles at the edge of the field. This so-called dome aeration technology has been adopted from waste management for the drying of wood chips and is patented at the Technical University of Dresden. The drying process is driven by self-heating of the material and the subsequent advection of the moisture through pipes. The aeration is just driven by the temperature difference between the inside of the pile and the surroundings (Brummack 2008). During the drying process, the water content is reduced from 50% to 25%. Dry mass losses of 3% are assumed due to decaying processes and losses during the removal of clamps. After drying, the poplar chips are transported 50 km by truck to their destination. Table 1 provides an overview on the operation steps of SRC management and their fossil fuel use.

Background data on the production of chemicals and fossil fuels, as well as on transport processes, were taken from the GaBi 4 database (PE, LBP 1992–2008). For the transport processes distance, load and the driving share of different street categories have been adapted. The production of the herbicide was modeled after Audsley et al. (1997). Fossil diesel use for field preparation and weed

Table 1 Fossil fuel use for the operation steps of short-rotation coppice cultivation and processing

Operation	Operation steps	Fuel use [lha^{-1}]	Annotation
Plantation establishment	Soil preparation; herbicide spraying; planting; weed control in the first year	40	Spraying of glyphosate; 10.458 cuttings per hectare
Harvesting; stool removal		64; 462	Forage harvester with wood cutting attachment stool removal by mulcher and rotary tiller
Drying/storage; road transport	Heaping the piles by front loader transport by lorry, payload 27 t	1; 2.5 or 5	Transport distance 50 km to CHP plant; 100 km to BtL plant

control was taken from agricultural database (KTBL 2006). For planting, harvest and reconversion data were provided from field trials in eastern Germany.

2.3 Biomass energy conversion model

The environmental impact of heat and power generation or FT diesel production from poplar chips are assessed by considering the biomass production chain as described above. Primary data on the technical properties of a CHP plant in southern Brandenburg were used to model the conversion into power and heat (Press (2007), personal communication via fax 28.09.2007; Fiedler et al. 2006; Stadtwerke Elsterwerda 2007). The CHP plant produces thermal energy of 44 and 12 MW electrical energy with an overall efficiency of 87% and with an electrical efficiency of 31%, in particular. The ash is transported over 50 km by lorry for disposal. The ash is deposited at a landfill site. Data on the resulting emissions are derived from literature sources (Jungbluth et al. 2002). The net calorific value (NCV) of biomass fuels depends on their water content. The NCV of poplar chips at 25% water content in this study was calculated by adopting the formula by Kaltschmitt and Hartmann (2001) and amounts to 13.3 MJ kg^{-1}.

The environmental impacts of diesel production from SRC were analyzed in the example of the Choren Carbo-V-Process. In a two-step process, biomass is firstly gasified, and (in the Fischer–Tropsch synthesis) secondly, the synthesis gas is liquefied at high temperature and pressure with the addition of oxygen, nitrogen, hydrogen, and catalysts. The distribution of the produced fuel and its use in a passenger car is also included into the model. The process will be briefly illustrated in the following figure (Fig. 2).

There are different ways to steer the FT diesel synthesis process. They differ in terms of the origin of the required chemicals. In this study, it is presumed that the required chemicals like oxygen, nitrogen, hydrogen, as well as heat and electricity are obtained from the biomass during the process. This version of process control is currently practiced and being tested by Choren (Choren 2009). Biomass consumption for this process version is higher than for versions with an external feed of electricity, steam, and chemicals. Therefore, the input–output ratio on biomass (kilograms oven dry weight) needed for 1 k FT diesel is 6:1. Information on the process and its stock and energy flows were derived from Baitz et al. (2004) and Choren (2009).

2.4 Allocations

For the CHP scenario, the environmental impacts are allocated between the two products heat and power according to their exergy content. The exergy describes the available energy, which is embodied in heat and power and is available to be used. One-kilowatt-hour power has the exergy content 1. The exergy content of the heat depends on its temperature in comparison to the surrounding. In this model, the released steam has a low temperature (110°C) and the surrounding temperature on average 10°C; hence, the exergy content of the heat equals 0.26 (see Fig. 3 for details). The allocation on an exergy basis allows the comparison of two products with unequal use, like heat and power. By employing the allocation on an exergy basis, the main emphasis is put on the product power, which results in relatively high impact values for power. A sensitivity analysis showed that employing both, allocation on a caloric basis and on market values, would result in lower impact values for power than the below presented.

For the FT diesel production, all environmental burdens within the life cycle are attributed to the unit of FT diesel. Co-products which occur during the production process, like electricity and heat, do not leave the system. They are re-used within the process cycle, and, therefore, an allocation of burdens is not required.

3 Environmental impacts

3.1 Biomass production

In this chapter, at first, the results of the environmental impacts of biomass production and its distribution will be presented. The functional unit is 1 odt of poplar chips.

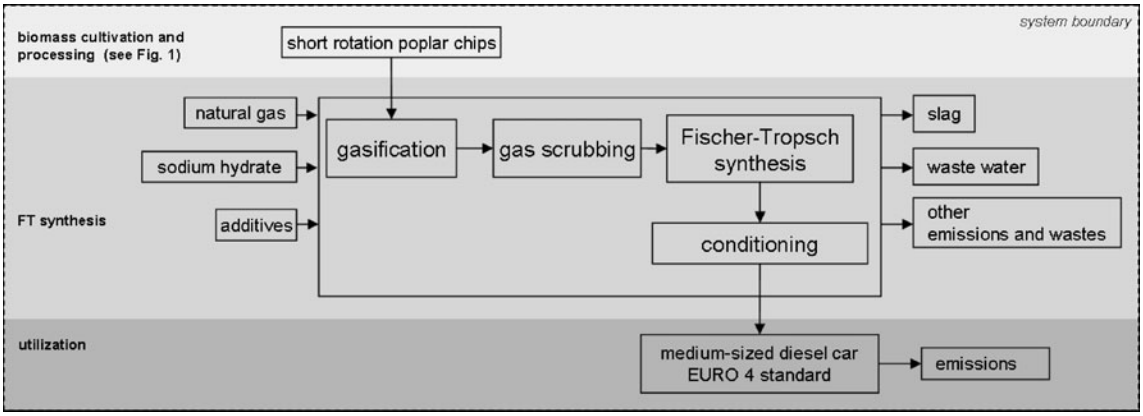


Fig. 2 System boundaries and process steps of FT diesel production and usage

Subsequently, the environmental impacts of heat and power generation from the poplar chips and the production of FT diesel, respectively, are described in paragraph 3.2. For the scenario of biomass conversion in the CHP plant, the functional unit is 1 MJ of heat or power. For the scenario of FT diesel, the environmental impacts are displayed per 100 km driven in a medium-sized diesel car.

3.1.1 Energy use

For the assessment, only the use of non-renewable energy has been considered. Renewable energy in form of solar radiation which initiates the build-up of tree biomass was not accounted for in the balance. Table 2 displays only the consumption of fossil energy. Fossil energy is used directly for running the machines and in the background system for the production of fuels, herbicides, and auxiliary materials. Most fossil energy is used during transportation of the harvested poplar chips and for reconverting the field at the end of coppice cultivation. Compared with this, the establishment of the short-rotation plantation and its harvest require less fossil energy input.

No additional fossil energy is needed during the drying process. As described above, drying is only driven by the spontaneous self-heating of the chips. Fossil fuel is consumed by the front loader which piles up the chips.

Production and distribution of 1 tonne (odt) poplar chips requires about 432 MJ non-renewable energy, mainly diesel fuel. One oven dry tonne of wood embodies 18,500 MJ of energy. This leads to an energy ratio of 43:1.

Fig. 3 Calculation of the Carnot factor to determine the exergy content of the heat. Temperatures have to be put in the formula in Kelvin

$$\eta_C = \frac{T - T_u}{T}$$

η_C: *Carnot factor*

T: steam temperature (K)

T_u: *surrounding temperature (K)*

3.1.2 Environmental impacts of biomass production and processing

In Fig. 4, the environmental impacts are shown for the four selected impact categories in total numbers and divided into the production steps. The pattern, how the environmental impacts are allocated to the process steps, resembles the pattern of energy consumption.

Since the impacts are mostly induced by the use of fossil fuels, transport, field recovery, and harvest have the greatest share of total environmental impacts in almost all categories.

After normalization (Fig. 5), a comparison of the environmental impacts across the impact categories is possible. The normalization helps to better understand the relative importance and magnitude of the category results Guinée (2002). The normalization applied in this study refers to the total environmental impact of each category in Germany in the year 2006. The normalization factors have been adopted from the GaBi database (PE, LBP 1992–2008).

The normalization (Fig. 5) shows that the acidification potential (AP) is the most important impact category related to the total reference values on national level. Mainly nitrogen oxides (NOx) and, to a smaller extent, sulfur

Table 2 Consumption of fossil energy for cultivation and processing of 1 oven dry tonne (odt) of short-rotation poplar chips

	Fossil Energy [MJ odt^{-1}]	Share [%]
Field preparation incl. weed control	31, 9	7
Harvest	79, 9	18
Transport	142, 3	33
Storage/drying	45, 2	10
Stool removal	132, 5	31
Total	431, 8	100

Figures are displayed separately for the single production steps in total and relative numbers

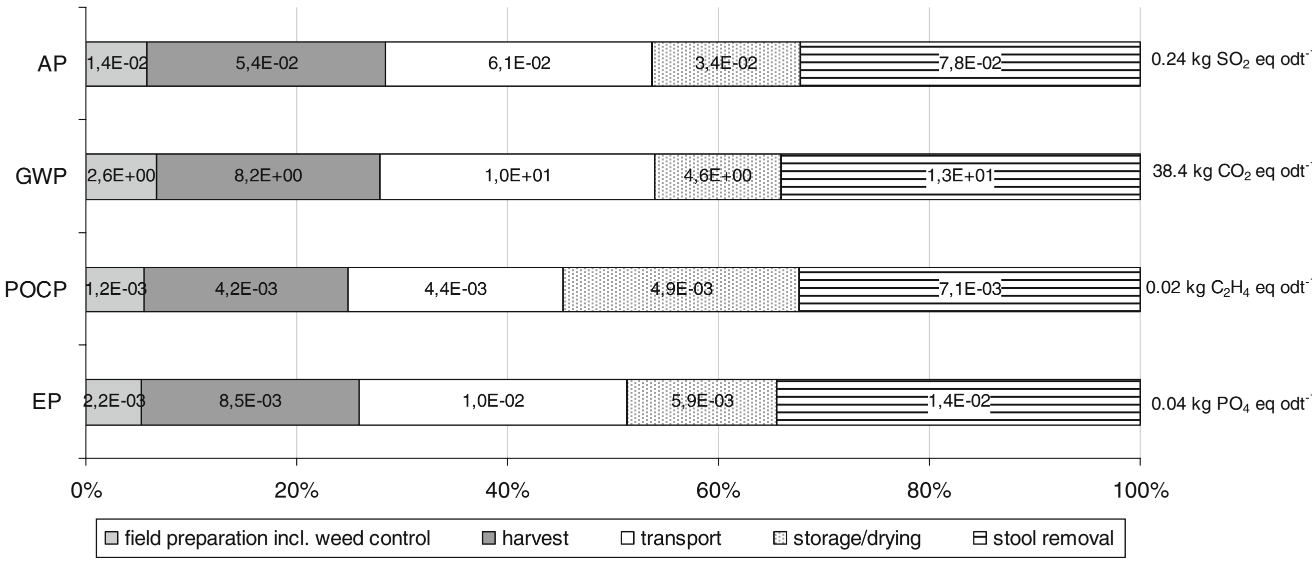


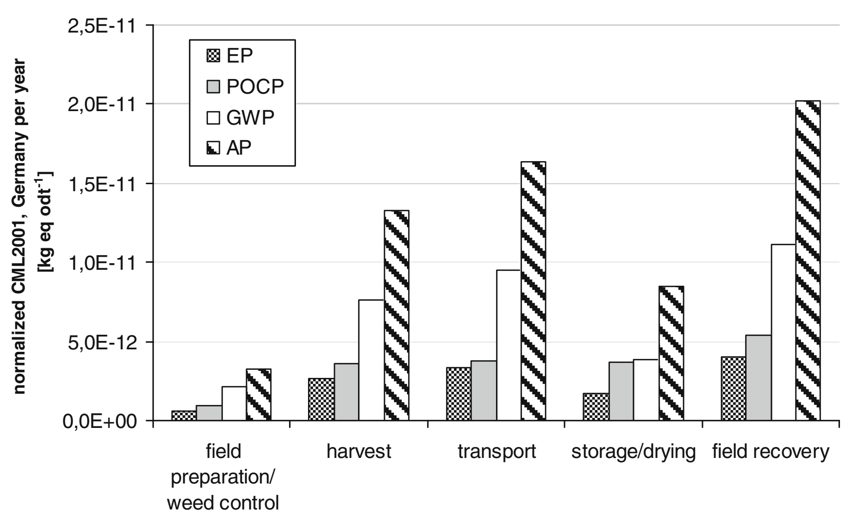
Fig. 4 Environmental impacts of the production and processing of 1 odt short-rotation poplar chips, given in total numbers and allocated to the single process steps. *AP* acidification potential, *GWP* global warming potential, *POCP* photochemical ozone creation potential, *EP* eutrophication potential)

dioxide (SO_2), which result from the combustion of fossil diesel fuel, are responsible for the AP. Therefore, energy-intensive sub-processes like stool removal or transport have the highest impact values in all categories. Eutrophication and POCP are less important relative to the reference values.

3.1.3 Impact of land use

In an LCA in the field of agriculture, environmental impacts from land use and land use change should be taken into consideration in addition to the “classical” impact categories Milá i Canals et al. (2007). Environmental impacts arising from land use and land use change are, for example, changes in soil properties or changes in animal or plant species composition. Suitable methodologies as well as sufficient data for a complete assessment are lacking at this point of time. For example, the development of soil carbon stocks and the accumulation or release of carbon from soils has not been very well-documented. These processes are very much dependent on the site, and its parameters show a large variation. Nevertheless, CO_2 released or fixed due to land use changes may have a considerable share in the indicator results of global warming potential. Hereafter, difficulties and possible solutions of assessing land use are exemplified by integrating soil carbon pool changes into the assessment. Neither the development of the water balance nor the impacts of indirect land use change due to SRC cultivation on agricultural fields were part of this study. Indirect land use change effects are supposed to be inconsiderable because it

Fig. 5 Normalized environmental impacts of the process steps of SRC production and distribution per oven dry tonne (odt)



was assumed that the plantation is established on a set-aside area.

Soil carbon change There are several studies examining the soil carbon changes under SRC, but there are varying results (Sartori et al. 2007; Grigal and Berguson 1998; Jug et al. 1999; Heller et al. 2003). Some of them find declines in soil carbon contents under SRC and some find increases.

In the directive on renewable energies, the European Commission provides default values for calculating the changes in soil carbon pools due to land use changes (European Commission 2008, Appendix VII). The following example (Table 3) demonstrates the application of these figures for calculating an expected rate of soil carbon changes under short-rotation poplar coppice on agricultural lands. For the initial state, before coppice establishment, the value for “arable” land is chosen. The value for the state of poplar cultivation corresponds to the default value for “lightly forested area”. In the table, the development during a 20-years period with an increment of 8 t atro ha^{-1} $year^{-1}$ is presented.

The resulting negative figures indicate a carbon stock increase in soil and vegetation after land use change. In total, 99 tonnes of carbon are gained per hectare. If the amount of carbon dioxide which is stored in the above ground biomass (80 t C ha^{-1}) is subtracted from this overall carbon gain, an increase of soil carbon stocks by 19 t C ha^{-1} can be presumed. From that, it follows that, in our case, 0.12 tonnes of carbon are accumulated in the soil per oven dry tonne of biomass; this equates to 0.44 tonnes of carbon dioxide per oven dry tonne. This uptake would overcompensate for the complete greenhouse gas emissions of biomass production and distribution (compare Fig. 4).

3.2 Biomass utilization

3.2.1 Environmental impacts of heat and power generation

The short-rotation poplar chips can be used for heat and power generation. It is presumed that they feed a CHP plant. The cogeneration plant generates 4,124 MJ power and 7,450 MJ heat from 1 tonne of poplar chips with a water content of 25%. Table 4 shows the environmental impact of the whole bioenergy chain, from field production to combustion allocated to heat and power.

Table 3 Calculation of carbon stock changes in vegetation and soil within 20 years after the establishment of SRC with the help of the EU default values (European Commission 2008)

	t C ha^{-1}	t C odt^{-1}
Default value “arable”	82	
Default value “lightly forested area”	181	
Carbon stock change in soil and vegetation	−99	−0.62
Carbon stored in the vegetation (tree biomass)	−80	−0.50
Theoretical carbon stock change in the soil	−19	−0.12

The allocation of environmental impacts is carried out on the basis of the proportion of power and heat production, weighted by the temperature of the latter (see 2.4). The cogeneration plant is run as a power plant, where the waste heat is used for district heating. Because of the relatively low temperature of distributed heat, the majority of environmental burdens are allocated to the power. A variation of plant operation would lead to reversed impact indicator results for heat and power. Furthermore, a higher degree of efficiency would result in lower-impact indicator results and vice versa.

The global warming potential comprises only greenhouse gas emissions from fossil origins. Carbon dioxide emissions originating from the combustion of the poplar biomass have not been accounted for the global warming potential. Carbon dioxide fixed during tree growth, which is released during the combustion, adds up to zero in the balance (see: Rabl et al. 2007). Hence, the global warming potential of the poplar chips supply chain exceeds the GWP of the combustion process.

After normalization, the environmental impacts of the supply chain and the subsequent combustion process are compared. Thus, it appears that the environmental impacts of the poplar chips supply chain are low compared with the impacts occurring due to the biomass conversion process. Important impacts of the combustion are mainly acidification as well as eutrophication.

3.2.2 Environmental impacts of FT diesel production

The conversion process which was examined here needs only a few operating supplies like natural gas and sodium hydroxide. All the other operating supplies (electricity, oxygen, nitrogen, and hydrogen) are generated from the biomass within the process cycle. Therefore, biomass consumption per liter FT diesel produced is higher for this process option than for other possible kinds of process control. Figure 6 presents the normalized impact indicators for the whole FT diesel system from field preparation to car operation at a distance of 100 km.

The global warming potential found is quite low because of the above-stated process control. A different process control would result in higher environmental impacts. As argued in the CHP process in Article 3.2.1, within the assessment of FT process, carbon dioxide emissions originating from poplar biomass are not accounted for their global warming potential either. This corresponds with the methodology suggested by the European Commission for

Table 4 Impact indicator results for heat and power generation from short-rotation poplar

Impact category	Unit	Per MJ power	Per MJ heat
Eutrophication (EP)	kg PO_4 eq	3.5E-05	9.4E-06
Photochemical ozone creation (POCP)	kg C_2H_4 eq	1.3E-05	3.5E-06
Global warming (GWP)	kg CO_2 eq	6.3E-03	1.7E-03
Acidification (AP)	kg SO_2 eq	1.9E-04	5.1E-05

assessing global warming impact of biofuels (European Commission 2008, Annex VII).

Important environmental impacts occurring during FT diesel generation are eutrophication and acidification and, to a minor degree, the photochemical ozone creation. Eutrophication and photochemical ozone creation also arise due to car operation on FT diesel. The carbon dioxide emissions from the combustion of the FT fuel in the car are not regarded for their global warming potential. In the table below (Table 5), the non-normalized values for production and utilization of FT diesel from short-rotation biomass are displayed.

Following the EU methodology on assessing greenhouse gas emissions from biofuel production, the results should be stated in grams CO_2 equivalent per unit energy content in the biofuel (megajoules). By applying the value in Table 5 to this functional unit, the global warming potential amounts to 9.6 g CO_2 eq per MJ biofuel.

3.3 Comparison of environmental impacts bioenergy vs. fossil energy

The following figure (Fig. 7) compares the environmental impacts of power generation from short-rotation poplar chips and the average power grid generation in Germany, as well as power generation from natural gas and lignite.

Huge differences can be found between environmental impacts of the average power generation and power generation from poplar chips especially in terms of global warming potential and acidification potential. The photochemical ozone creation potential is reduced as well when power is generated from poplar chips rather than average power generation. The eutrophication potential of power generation from poplar chips exceeds the potentials of the average power generation.

In a closer look at some specific fossil resources, it appears that, in terms of global warming potential and photochemical ozone creation, the environmental impacts of power generation from poplar chips are much lower than in the use of lignite or natural gas. The eutrophication potential of power from poplar chips is slightly higher than the average German power mix and significantly higher than that of power from natural gas. However, power generation from lignite has a higher impact in terms of eutrophication than power generation from poplar chips. In terms of acidification potential, power from poplar chips is more favorable than power from lignite but inferior to power from natural gas.

There are various possibilities to compare the environmental impacts of the different utilization paths of short-rotation biomass. In the present study, each conversion path of short-rotation poplar is compared with its fossil reference. With this comparison, no conclusions on the most favorable utilization path of short-rotation wood in terms of reducing greenhouse gas emissions can be drawn. The comparison of the different conversion paths among

Fig. 6 Normalized indicator results of FT diesel production and utilization in a medium-sized diesel car at 100 passenger kilometers

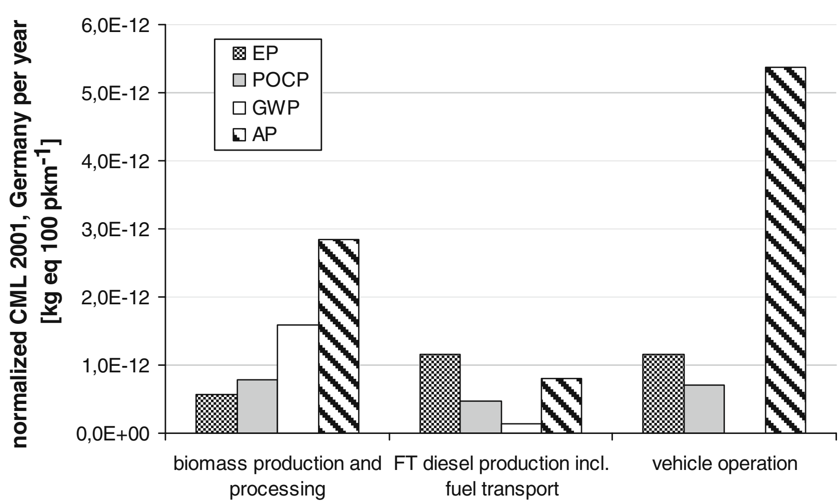


Table 5 Non-normalized impact indicator results of FT diesel production and utilization from short rotation poplar

Impact category	Unit	Per passenger kilometer
Eutrophication (EP)	kg PO_4 eq	9.9E-03
Photochemical ozone creation (POCP)	kg C_2H_4 eq	2.5E-03
Global warming (GWP)	kg CO_2 eq	2.0E+00
Acidification (AP)	kg SO_2 eq	3.6E-02

themselves is complex because the products heat, power, and diesel fuel feature different conveniences. It is possible to compare these different conversion paths on an area-related basis. For this, it is necessary to switch the functional unit into 1 ha covered by SRC where a certain amount of poplar wood is produced. The energy products made from this wood are then compared, for example, in terms of overall greenhouse gas emissions or gains of usable energy. From an emission-saving point of view, it would be beneficial to convert short-rotation biomass into heat and power and not into FT diesel. If just energy production over the whole life span is compared on a megajoule basis, combined heat and power generation would also be favorable because of a higher energy gain per hectare than the FT diesel conversion path.

4 Comparison to other studies and discussion

The first part of the study assessed the fossil energy use and the environmental impacts of producing and distributing short rotation poplar chips. In this assessment, a ratio of bioenergy output to fossil energy input of 43:1 was found (see 3.1.1). A study by Heller et al. (2003) found an energy ratio of 55:1 for short-rotation willow cultivation in the USA, though Heller et al. (2003) assumed a higher yield of 12 odt $ha^{-1}yr^{-1}$. In a study by Matthews (2001), which assesses short-rotation poplar and willow, energy ratios in a range between 20:1 and 64:1 have been calculated. The value found in the present study lies within this range. Energy ratios between 22:1 and 28:1 have been examined for different management scenarios in Belgium by Dubuisson and Sintzoff (1998). These scenarios take the application of fertilizer and fencing into account. The net energy gain found in the present study is higher because fertilization, and construction of machines and infrastructure have not been taken into account.

In order to compare the presented impact, assessment results to previous studies the GWP of biomass production and distribution are translated to a functional unit based on the energy content of the produced biomass. The GWP found in the present study related to the net energy stored in the produced biomass (MJ_{net}) results in 2.08 g CO_2 eq MJ_{net}^{-1}. Gasol et al. (2009) found a slightly lower global warming potential of 1.90–1.98 g CO_2 eq MJ_{net}^{-1}, although the input of fossil energy over the whole timeline is higher than in the present study. But, due to a higher overall yield of the poplar plantation, the fossil energy use and its associated emissions in Gasol et al. (2009) are allocated to a greater amount of biomass.

Gasol et al. (2009) also assessed other impact categories like the eutrophication and acidification potential. They found slightly higher values for AP (0.29–0.30 kg SO_2 eq odt^{-1}) and EP (0.06 kg PO_4 eq odt^{-1}) than the present study. In the present study, an acidification potential of 0.24 kg SO_2 eq and an eutrophication potential of 0.04 kg PO_4 eq per odt have been calculated for biomass production and distribution. This deviation could be explained by the consideration of herbicides, pesticides, and fertilizer use within the model of Gasol et al. (2009). Heller et al. (2003)

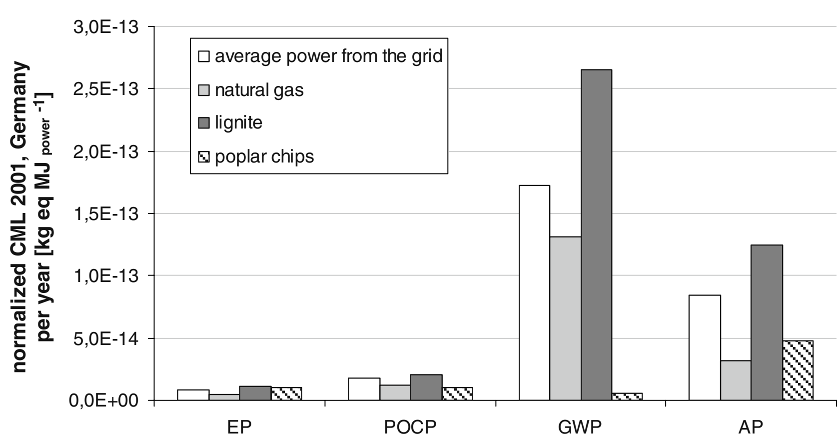


Fig. 7 Normalized impact indicator results of generation of 1 MJ power from different fossil resources and the average value for power from the grid in Germany

found a similar eutrophication potential (0.047 kg PO_4 eq odt^{-1}), but an almost twice as high acidification potential (0.47 kg SO_2 eq odt^{-1}) than the present study.

But, Gasol et al. (2009) surprisingly calculated a much lower photochemical ozone creation potential. Emissions contributing to the POCP, like nitrogen oxide and carbon monoxide, are mainly caused by fossil fuel combustion processes. The low POCP value cannot be explained only by the higher yield in the model of Gasol et al. (2009). A sensitivity analyses between the fertilized and the non-fertilized case showed also, for the present study, lower POCP values in the fertilized case. This is due to the release of nitric oxide on the fertilized field. During fertilizer production and its application, nitric oxide is released, which counteracts the creation of ozone by forming nitrogen dioxide and oxygen. This diminishes the POCP of the fertilized version.

The second part of the here-presented study assessed the impacts of the whole bioenergy chain from short-rotation poplar. There are some further studies investigating the environmental impacts of the whole chain of bioenergy generation from SRC. Mostly, they are focussed on the assessment of energy consumption and carbon dioxide emissions or global warming potential.

Jungmeier and Spitzer (2001) assessed global warming potential for combined heat and power generation from SRC of 0.02 kg CO_2 eq per MJ of heat and power. In the present study, a global warming potential of 0.01 kg CO_2 eq per MJ has been assessed for both products.

There are some studies investigating the FT diesel production from SRC (Edwards et al. 2008; Jungbluth et al. 2007, 2008; Reinhardt et al 2006). Edwards et al. (2008) are presenting their results related to one MJ biofuel. They found an average global warming potential of 9.6 g CO_2 eq MJ^{-1} within a range of 5.4 to 18.8 g CO_2 eq MJ^{-1}.

Jungbluth et al. (2008) presented their results related to passenger–kilometer (pkm) and calculated a global warming potential of 0.09 kg CO_2 eq per pkm. Translated to this functional unit, with a passenger load of 1.59 persons per run, the global warming potential found in the present study amounts to 0.01 kg CO_2 eq pkm^{-1}. Jungbluth et al. (2008) consider the application of pesticides and fertilizer as well as the production of machinery and infrastructure within their assessment.

Reinhardt et al. (2006) only present the environmental impacts in figures normalized proportionately to the fossil fuel use. As with the present study, Reinhardt et al. (2006) found a higher eutrophication impact of FT diesel from SRC in comparison to fossil diesel use. But, unlike the present study, they also calculated a higher acidification potential for FT diesel use than of fossil diesel use. They explain their relatively high acidification potential by nitrogenous emissions from fertilizer production and application. The sensitivity analysis of the own results showed higher AP values for the fertilized field as well; but, nevertheless, the AP of FT diesel use does not exceed the AP of fossil diesel use. This was due to a high level of acid emissions during car operation by fossil diesel. The tendency of the further impact indicator results found by Reinhardt et al. (2006) accords with the findings in the present study. Global warming potential and photochemical ozone creation potential of FT diesel use are found to be lower than those of fossil diesel use.

5 Conclusions and recommendations

The environmental burdens of cultivation and harvest of short-rotation poplar wood are low, if they are related to the biomass produced within the entire lifespan. Usable energy produced from this biomass causes fewer environmental impacts than energy generation from fossil resources. As found in the present study, the environmental impact power generation from short-rotation biomass are lower than average power from the grid in most of the examined categories, besides eutrophication potential. Compared with power generation from natural gas, power from poplar chips is favorable only in terms of POCP and GWP. The eutrophication potential and the acidification potential of power from poplar chips exceed the burdens of power generation from natural gas.

FT diesel from SRC also has lower environmental impacts than fossil diesel in almost all categories beside eutrophication. In terms of saving greenhouse gas emissions it would be favorable to convert short-rotation poplar into heat and power instead of producing FT diesel. However, FT diesel from short-rotation poplar would meet the European requirements for greenhouse gas emission reductions of biofuels. The EU directive claims a GHG reduction of 35% by the production and use of biofuels instead of fossil fuels (EU Commission 2008). FT diesel saves 93% of GHG emissions compared with fossil diesel.

The comparison to previous studies is valid only to some extent, if their system boundaries and assumptions differ. As explicated above, the inclusion of fertilizer, pesticide and herbicide application can result in huge differences of the impact category results. Production and application of nitrogen fertilizer, for example, release greenhouse gas emissions, which increase the GWP value. In the presented study, short-rotation coppice cultivation was assumed without fertilizer application, which is possible for poplar, but not for willow cultivation. If short-rotation poplar would be produced with the help of fertilizer, e.g., the global warming potential would increase by a factor of 1.5 and the eutrophication potential by a factor of 1.7 (q.v. Rödl 2008). Additionally, the inclusion of machinery construc-

tion, different management regimes and differing engaged machinery lead to divergent assessment results. Furthermore, the yield influences the impact indicator results. The more biomass is produced, the lower the environmental impacts of plantation establishment and its reconversion, when the results are allocated to the produced biomass or its energy content. Because transports have a huge proportion of the energy consumption, changes in transport distances would have a considerable influence on the results. The same is true for the weight of transported biomass, which depends on the water content. The higher the weight, the higher are energy consumption and environmental impacts.

Besides the selection of the allocation method, it has a huge influence on the impact assessment results. The method should represent the today's preferences by allocating the major burdens to the focused product.

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